Pressure Difference-Based Sensing of Leaks in Water Distribution Networks

by

Pall Magnus Kornmayer

Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of

Bachelors of Science in Mechanical Engineering

at the

Massachusetts Institute of Technology

June 2011

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Abstract

Human society and civilization rely on the constant availability of fresh water. In regions where a local source of potable water is not available, a transportation and distribution pipe system is employed. When these pipes feature cracks, holes, or leaks, the result is a substantial waste of energy and natural resources. As communities grow the loss due to these flaws becomes more costly, and the motivation to detect leaks increases.

The purpose of this thesis project is to develop pressure difference-based sensing cells that can be used in an untethered leak-detection device. This device is to be deployed in water distribution networks to locate leaks so that water loss can be minimized. Design of these sensing cells and of the leak-detection device entails evaluating the size and shape of a leak's low-pressure region. In this paper, leaks are investigated in this regard and a number of different pressure difference-sensing sensor technologies are explored and evaluated.

A silicone-rubber deflecting membrane is selected for the application. The relationship between pressure-derived force acting on its surface and its maximum deflection is evaluated as a means of leak detection. Ultimately, testing reveals that these types of cells are simple and robust. While they deflect as anticipated, the formula used to predict their behavior does not fit the experimental results. It is concluded that this type of pressure difference-sensing membrane is well-suited for application within an untethered sensor, with the opportunity for deeper material selection and more accurate deflection analysis.

Thesis Supervisor: Sanjay E. Sarma
Title: Professor of Mechanical Engineering

Dedication

This paper is dedicated to the memory of Cheryl Ann Sgro-Ellis. As my 7th-grade science teacher, she guided my first science fair project and sparked a love for science and engineering. Without her inspiration I would not have come to MIT or have become the person I am today. For her mentorship I am deeply thankful.

Acknowledgements

I would like to thank the members of Professor Sanjay Sarma's group at the MIT Laboratory for Manufacturing and Productivity for their support and collaboration on this project. In addition to professor Sarma, I would like to thank Stephen Ho for his guidance and many helpful suggestions. I would also like to thank Sumeet Kumar and Benny Drescher for their collaboration on the project.

Personally, I would like to thank my family and peers who have supported me before, during, and after my studies at MIT. It is an honor to have had this opportunity, and I could not have achieved as much as I have without their unwavering support.

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1 Introduction

Human society and civilization rely on the constant availability of fresh water. In regions where a local source of potable water is not available, pipe systems are employed to bring the resource to local communities. When the pipe systems tasked with distributing this water are cracked, punctured, or leak, the result is a substantial waste of energy and natural resources. As cities continues to grow, the strain placed on aging distribution networks aggravates existing pipe problems and highlights the need for network repair or replacement.

1.1 Problem Scope and Common Causes

The problem of leaking distribution systems is not unique to a particular region of the world. Reports from North America and the Middle East indicate that a significant portion of treated water is lost in transport between the source and the consumer. In the United States, Vickers reports that water losses in US municipalities ranges from 15-25%.[1] A report by the Canadian Water Research Institute found that, on average, 20% of treated water in Canada is lost during distribution.[2] In the Middle East, a study of ten sample areas in the city of Riyadh, Saudi Arabia revealed that, on average, 30% of water was lost in transport due to flaws in the water distribution networks.[3] These alarmingly high figures provide a significant opportunity for improvement.

The flaws in water distribution pipes that account for these system inefficiencies can be caused by a variety of factors. The most common cause of these is faulty seals and failures at joint threads and pipe connections. Pipe deterioration can be caused by ground movement, corrosion, and the vibration and repeated loading associated with vehicle traffic.[4] Leaks are often the result of aging or poorly-constructed pipelines, material defects, mechanical damage, poorly-maintained valves and fittings, and inadequate corrosion protection. [5] While flaws in the physical piping system are not the only source of unaccounted water loss – other forms include metering errors, accounting errors, and theft – physical defects compose the majority of lost water. [4,6]

1.2 Current Methods of Leak Detection

There exist various methods for detecting leaks in distribution networks. Water audits can be used to estimate losses – the difference between the amount of water provided by the water utility and the amount of water record by water usage meters corresponds to the amount of water lost in transit. In district metering, certain sections (districts) of the distribution network can be isolated and analyzed in the same way to provide more meaningful insight into which portions of the network provide the largest contributions to water loss. [4,6]

While useful in analyzing which sections of pipe feature losses and warrant further inspection, examining meters does not provide helpful insight concerning the specific locations of leaks or how they might be repaired. There exist a number of alternative leak-sensing techniques that are based on the distinct physical effects of leaks. Infrared thermography is a technique whereby the temperature distribution of surface soil above a water network is analyzed. Water leaks from the buried pipe change the thermal characteristics of the site, and thermography can be used to locate leaks.[7] Injection of a tracer gas into a pipe network suspected of leaking is another technique. This lighter-than-air, non-toxic, water insoluble gas moves through the pipe, eventually escaping through the leak and penetrating the soil where it can be found with a sensitive detector. Ground-penetrating radar (GPR) can be used to detect underground cavities caused by leaking water.[8] These techniques provide the ability to determine the location of a leak within a specific pipe network, but can require sensitive or specialized instruments and a large degree of user interaction.

A successful, recently-developed method focuses on acoustic detection of leaks. This can be done in a number of ways, either through the use of hydrophones or listening rods, or geophones that listen for leaks in the ground above the pipe.[4] Leaks have a particular sound profile, and analysis of readings from acoustic instruments can give insight to the size and location of the leak. In-pipe hydrophone technology was implemented by the Sahara system, where a tethered sensor was inserted into 12-inch diameter water mains to detect leaks.[9] The maximum amplitude of the leak noise signal indicated the presence of a leak, and for certain operating pressures and acoustic characteristics the system was able to detect very small leaks.

The reliance of the Sahara system on a tether device increased the complexity of operation. With wireless data transmission, it has become possible to drop the tether system in favor of a device that can move freely down the pipe, collecting acoustic data and relaying the information to an external device. Galleher and Kurtz described such a device for use in 10-inch diameter pipe systems.[10] An accelerometer, power source, acoustic sensor, microprocessor, and ultrasonic transmitter onboard the device relayed leak information to ultrasonic listening devices placed along the pipe.[11]

Chatzigeorgiou *et al.* describe an experiment in which an in-pipe acoustic sensor was used for small-diameter pipe applications. Using a 4-inch distribution network, the team from MIT targeted the losses associated with leaks in smaller water pipes and sought to develop an understanding of the acoustic signals generated from leaks of various size, with a hydrophone at various locations up- and down-stream of the leak.[12]

Consultation with members of the MIT team revealed a few shortcomings of the hydrophone system. In many scenarios, the signal-to-noise ratio of the sensor was low; processing the hydrophone data required calibration for the pipe system being tested; and "leaks at pipe pressures less than 1-bar are almost acoustically undetectable."[12]

1.3 Physical Sensing in Smaller Pipes

Because of the problems associated with acoustic sensing in smaller (4-inch) distribution pipes, we decided to investigate different approaches. Detecting leaks in smaller pipes is appealing for a few reasons. It is true that larger pipes potentially leak a greater amount of water; however, for this reason they produce a noticeable drop in line pressure and flow rate that are quickly detected. As a result, large leaks are typically repaired shortly after they are found. Smaller pipe leaks, meanwhile, are not detected as easily and can go unrepaired for long periods of time as a result. The rate of water loss is not as high as in large pipes, but the loss over an extended period of time can account for more losses than larger distribution pipes.

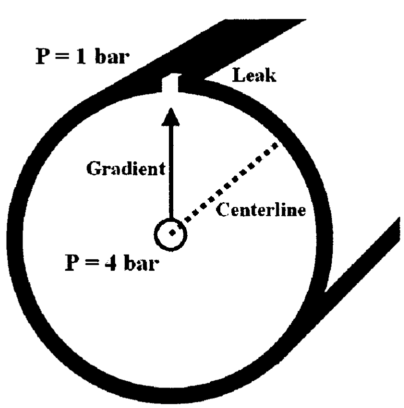

Figure 1: *Pipe cross-section showing an exaggerated pressure gradient induced when a leak occurs.*

Water is typically distributed at 50-60 psi, or roughly 4-bar. Outside of the pipe, the pressure is atmospheric, or 1-bar. When a leak is present, there exists an appreciable pressure gradient of roughly 3-bar between the centerline of the pipe and the leak, as seen in Fig. 1. It should be noted that the size of the centerline in the actual pipe is larger than represented in Fig.1, and that determining the detectable region of the gradient is the subject of Section 3.1. This gradient has the potential to be measured and quantified with some form of sensor. The goal of this work is to develop a sensor that can detect this radial gradient, and in the future can be integrated into a free-flowing device that navigates small-pipe water distribution networks. Ultimately, such a device will move through networks with minimal human interaction, detecting leaks and evaluating their severity, then transmitting information to engineers for analysis.

2 Objective

The objective of this thesis is two-fold. The first goal is to develop an understanding of the pressure profile of a leak in a water pipe. When designing a sensor that will move through a pipe, it is important to understand how large of an area of a pipe's cross-section is affected by a pressure gradient. This information dictates a number of the sensor's physical attributes, including how close to the pipe wall the sensor must be, and the number of sensor cells that must be arranged along its circumference. Specific questions to be addressed in Section 3 include:

- What is the characteristic shape of the low-pressure zone associated with a leak?
- How close to the pipe wall does the sensor need to be to lie within this zone?
- Does the presence of a second sensing channel affect the readings of a first?

The second goal is to design and construct an initial prototype for a leak-detecting sensor cell. Based on information gathered to understand the leak profile, different sensor cell designs and materials are evaluated and compared. An analysis of different configurations and parameters will lead to an optimized design that suits the sensor application. Specific questions to be addressed in Section 4 include:

- What physical form should the sensor cells take?
- What materials should be employed in these sensor cells?
- How can the dimensions of the sensor cell be 'tuned' for different pressure gradients?

There are certain questions related to this sensor that are not addressed in this thesis, ranging from what form the device will take or how it will navigate the pipe networks. The focus of this work is to develop the sensor cells that will be used in the larger device.

3 Understanding the Leak

The first step when developing the sensor cells was to understand the nature of the leak that is to be detected. An experiment was designed to learn about the size and shape of the low-pressure region around a hole in a pipe, and also to learn about the possible affects that one sensing cell may have on an adjacent sensing cell.

3.1 Determining the size and shape of the low-pressure region

As illustrated in Fig. 1, there is a radial pressure gradient within a water pipe at the location of a leak. The centerline and gradient components of the figure were sized for emphasis, but in reality it was uncertain how much of the cross section of the pipe could be considered to be at mainline pressure. To say it another way, it is important to understand the size of the low-pressure region at a leak of a certain size, so that the sensor can be designed to measure within that region. Originally, it was believed that the size and shape of the low-pressure region was dependent only on characteristics of the pipe and the leak size; our results, however, indicated that the form of the low-pressure region was primarily dependent up on the shape of the sensor used. This experiment, for this reason, actually surveys how the shape of the leak-sensing device affects the form of the low-pressure region.

3.1.1 Experimental Setup

These experiments employed a 4" diameter capped PVC pipe, seen in Fig. 2, drilled with small holes from 2- to 5-mm in diameter in 1-mm increments to simulate leaks of various sizes. This experiment was designed and its apparatus constructed by a former undergraduate student of the group, Sam Weiss. A test disc was machined from transparent polycarbonate with 7-mm channels bored along its circumference, as shown in Fig. 3. Each of these channels was fitted with a black nylon ball, which was free to move between the inner and outer diameters of the test disc to indicate the presence of a pressure gradient between the center of the pipe and the pipe wall. Additionally, to observe how the proximity of the channel mouth to the pipe inner diameter affected the ability to detect a gradient, each channel of the test disc was a different distance from the pipe wall. The distances ranged from 0- to 4-mm.

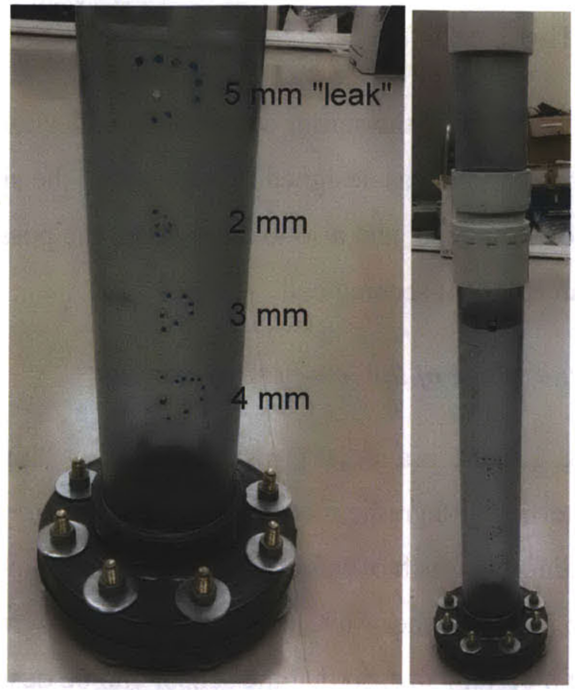

Figure 2. *The test pipe, which features four holes to simulate leaks of various sizes.*

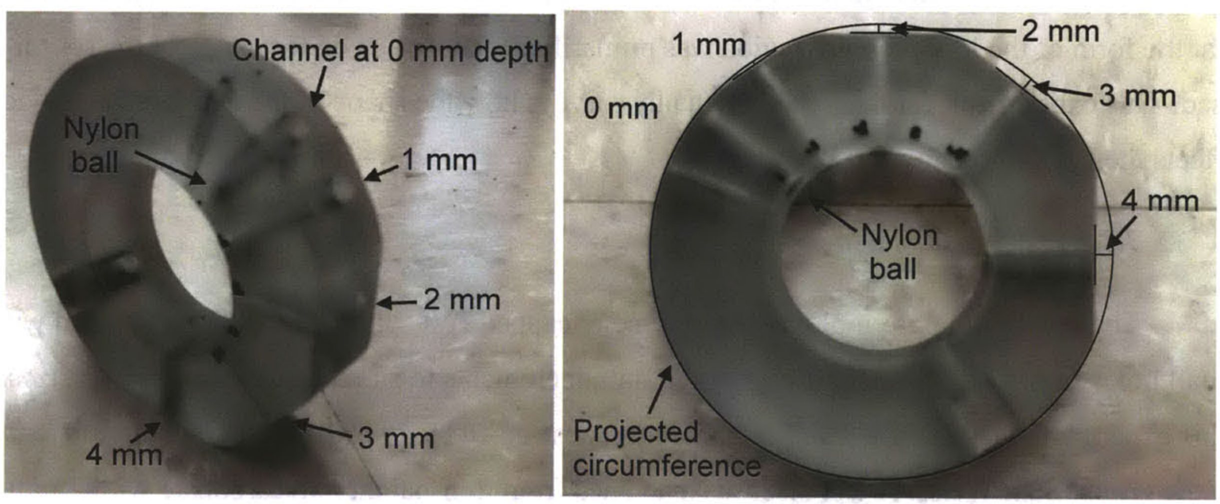

Figure 3. *The test disc, showing relevant features and dimensions.*

To conduct each trial, the test disc was installed in the pipe and the apparatus was connected to a water main. A magnet installed in the disc was used to manipulate its position in the pipe, bringing the test disc across the leaks so that the position of the nylon ball could be monitored. When the nylon ball shifted from the inner diameter of the test disc to its outer diameter, indicating the presence of a pressure gradient, a mark was placed on the pipe with a felt-tip pen. This procedure was repeated multiple times to describe the shape of the low-pressure region around the leak. Data was compiled for each leak size as well as each level of proximity between the channel outlet and the inner pipe wall.

3.1.2 Results and Discussion

Measurements for multiple channels revealed a common shape of the low-pressure region. Fig. 4 presents the data recorded for the 0-mm depth channel. The readings have been mirrored across the horizontal axis.

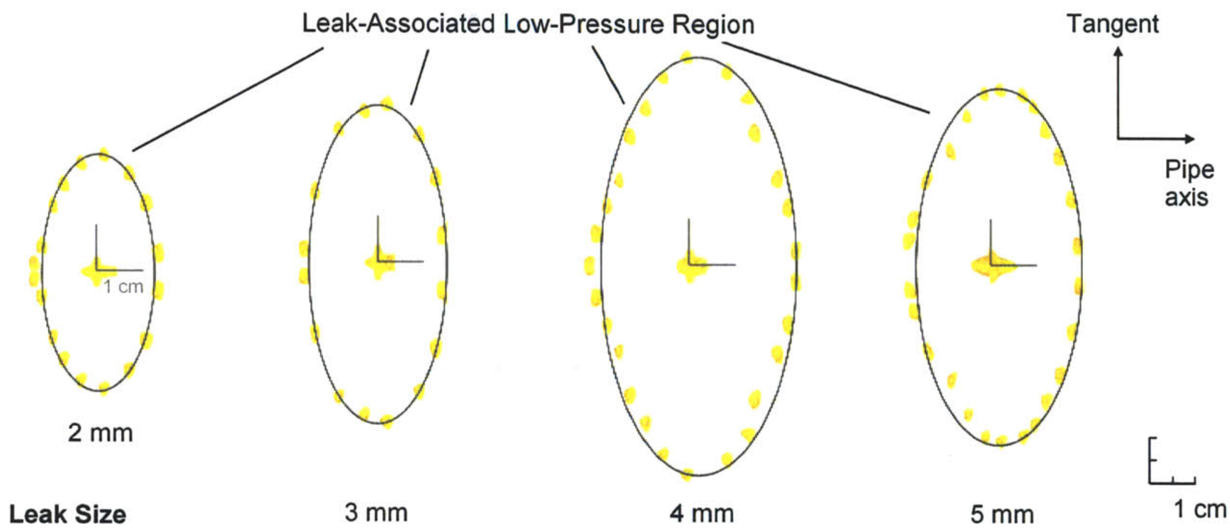

Figure 4: *The markings indicate an oval-shaped low-pressure region around a leak.*

A distinct oval-shaped low-pressure region is observed, giving insight into how the leak-sensing device might need to be designed. The dimensions of this characteristic oval help to determine how many sensing channels are required around the circumference of the device. The cause of this characteristic shape is explained in detail at the end of this section. Marks collected from all five channels were compiled, and are displayed in Fig. 5 below.

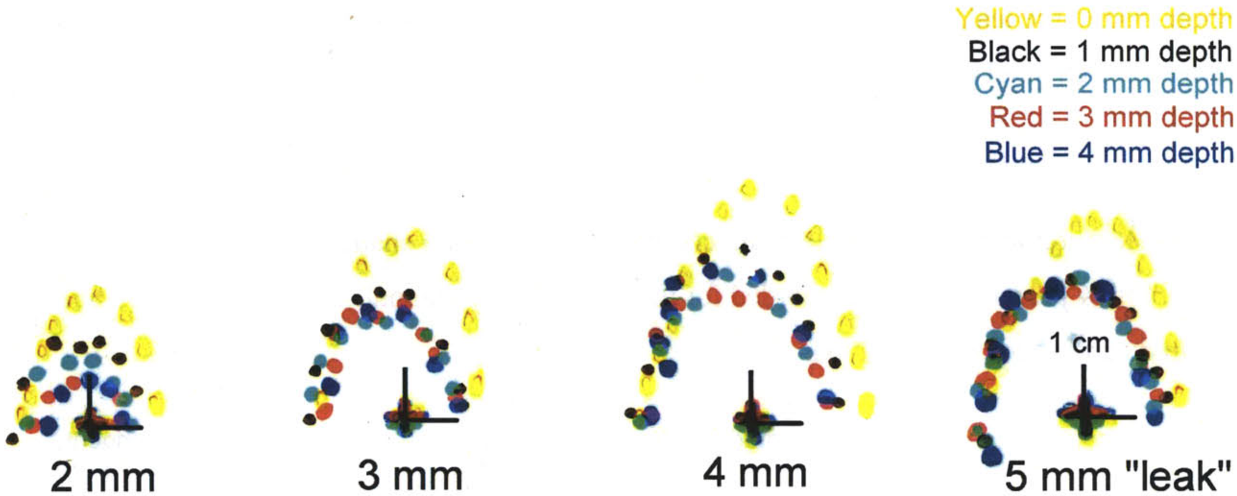

Figure 5. *The size and shape of each leak's low-pressure region. Note that the readings are not mirrored across the horizontal axis for this diagram.*

Whereas the results of a single channel were helpful in understanding the shape of the leak's low-pressure region, the compilation of readings taken at varying distance from the pipe wall help one understand how close the sensing channel must be to the leak to detect the associated pressure drop. This is an important parameter for designing a full-leak detection system, a design decision that affects the mobility systems and accuracy of the autonomous device.

The experiments produced the important realization that the presence of the test disc itself affected the size and shape of the low-pressure region. As seen in Fig. 4, there was an oval-shaped low-pressure region around the center of the leak. For a 2-mm leak, the minor axis of the oval shape is about 25 mm, compared to the 24 mm width of the test disc, illustrated in Fig. 6. The oval's major axis is elongated because the test disc's circumference is relatively close to the wall of the pipe there. While the size of the oval's minor and major axes changed with the size of the leak under examination, the oval shape remained intact and simply scaled in size.

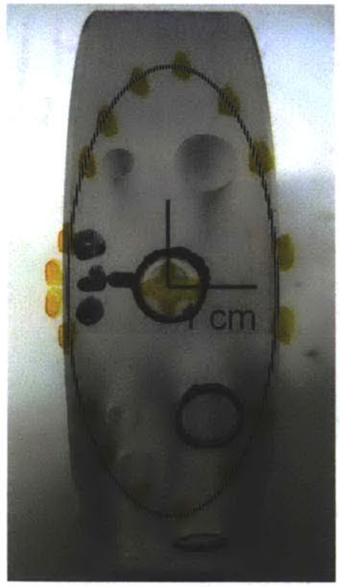

Figure 6: *Observed low-pressure region overlaid on the test disc.*

This important observation raises a design constraint on the device, and gives insight into one way that the size of the low-pressure region can be manipulated. Designing the sensing device in a certain way can either enlarge or diminish the low-pressure region, optimizing performance.

3.2 Exploring the effects of a second channel in close proximity

3.2.1 Experimental setup

The concern was raised during experimentation that the presence of a second channel in close proximity to the first sensor cell channel may affect the readings of the first. To test this hypothesis, the test disc was modified as seen in Fig. 7. A second set of channels was machined alongside the first set, and the procedure was repeated to determine whether there was a change in the shape and size of the region of leak detection.

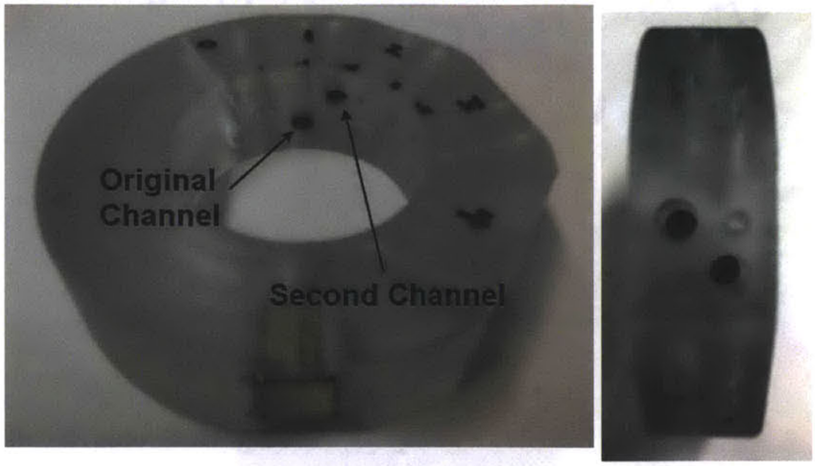

***Figure** 7. The modified test disc, featuring a second set of channels alongside the first.*

3.2.2 Results and Discussion

The data gathered in this second set of trials produced two important results: it demonstrated that a second channel had a negligible effect on the leak-associated low-pressure region of a first channel, and confirmed our conclusion that the presence of the test disc was affecting the shape of the region.

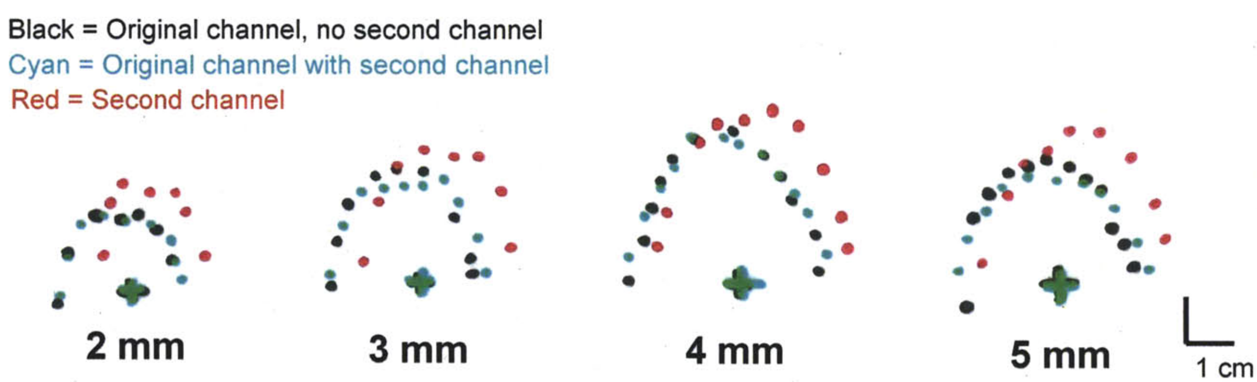

***Figure 8:** The region of low pressure around leaks of various size for a sensing channel 1 mm from the pipe wall.*

It can be seen from Fig. 8 that the presence of a second sensing channel had little to no effect on the region detected by the original channel. This gives us confidence moving forward that the leak-sensing device, if it were designed with multiple channels in close proximity, would capture data with high resolution.

The region of low pressure recorded with the second channel can be seen in Fig. 8 to be of similar oval shape to the original measurement, but translated diagonally. This corresponds to the location of the second channel in relation to the first on the disc itself, which is visible in Fig. 7. This result lends support to the idea that the presence of the test disc affects the low-pressure region as discussed in Section 3.1.2 because the sensitivity drop is related to the presence of disc material over the leak location. Fig. 8 shows that the region of low pressure on the left of the sensing channel is smaller than the region on the right; this is consistent with the location of the second channel and its relation to the edges of the disc, seen in Fig. 7. This confirms the observation that the shape of the disc has an affect on the behavior of the low-pressure region.

4 Developing the Sensor

In Section 3, we conducted experiments on leaks of various sizes to gain an understanding of the size and shape of the leak-associated low-pressure region. The data collected provides the first physical requirements of the design of the untethered device: proximity of the sensor to the pipe wall, and radial distribution of sensing cells. In this section, we develop a design for these sensing cells, testing different sensor configurations and materials to achieve an effective solution.

4.1 Design Process

The first step in the design of the sensing cell is to define how it will be implemented in the structure of the envisioned untethered leak detection device. Fig. 9 illustrates a potential form of this device and how the sensor cells will be integrated.

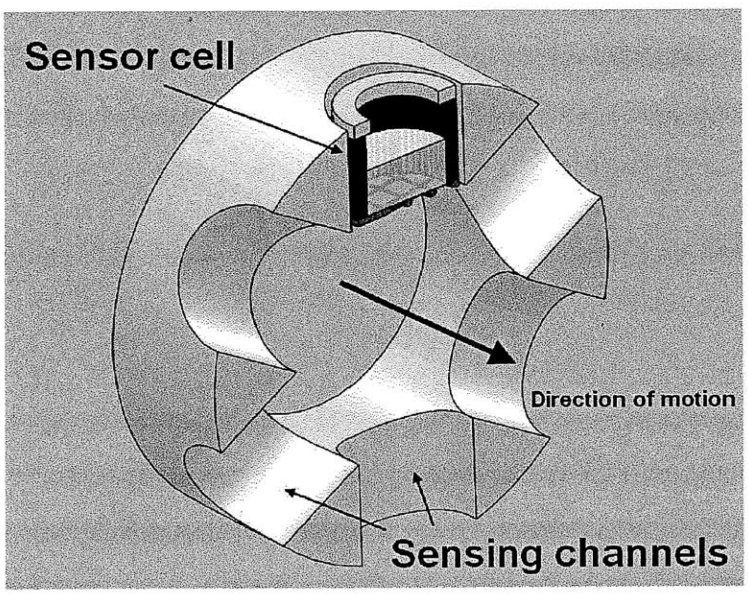

Figure 9: *A cut-away conceptual illustration of the untethered leak detection device, highlighting the integration of the sensor cells.*

As shown in Fig. 9, the device will consist of a number of radial channels. On the interior side of each channel, the water pressure is constantly at mainline pressure; the exterior side of each channel resides in the low-pressure region defined in Section 3. When a leak is present, there exists a pressure gradient within the channel that causes water to move from the interior side of the channel toward the exterior. The sensor cell is designed to detect that movement, either by measuring water flow or by deflection of a non-permeable material. Each channel of the device will feature one of these sensor cells.

4.1.1 Preliminary Sensor Designs

The sensor cell implemented for the leak-detecting device must be small, water-resistant, robust, and relatively simple. A hot-wire anemometer was considered to measure flow of water through the channel; these devices offer a very high precision reading of velocity of fluid flow. However, this type of sensor was determined to be prohibitively expensive and too fragile for this application. Hot-wire anemometers are difficult to build to a custom size and specification, and also do not give easily indicate the direction of fluid flow.

The next type of sensor considered, a strain gauge, focused on the installation of some type of deflecting material within the channel of the leak-sensing device. It was imagined that the strain gauge would be mounted on the surface of this material as seen in Fig. 10, and indicate the presence of a pressure gradient in the channel when the material deflected.

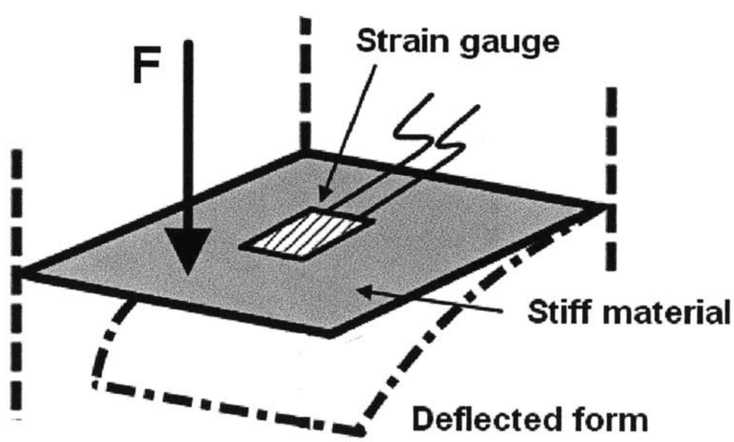

Figure 10: *Diagram of the proposed strain gauge application.*

Strain gauges are excellent for measuring small-scale deflection, offering a high degree of precision with a cost on the order of $5.00 USD per unit. For this precision, these gauges require high-precision measurement of small voltage changes on the order of a few millivolts, which would add to the cost. We determined that, for this application where the sensor cells are required for multiple channels on each device, the strain gauge was more expensive than desired. In addition, there were concerns about the ability of strain gauges to be used in fluid-focused applications.

While the strain gauge did not suit our particular application, the concept of a deflecting material anchored within the channels of the device appealed to us. Exploring the same type of mechanism found in strain gauges, we investigated the feasibility of "flex sensors" that were used in a variety of hobby robot applications and electronics projects. These sensors appealed to us because we did not need the high precision of a strain gauge for our binary sensor cell.

4.1.2 Evaluating the "Flex Sensor"

Strain gauges feature a conductive metallic foil that, when deformed, changes resistance in a way that can be measured. For small deflections, the amount of deformation correlates with a change in resistance and the relation can be used to quantify strain. Flex sensors, which we found while researching possible sensors online, work in a similar way. The Images Scientific Instruments website describes the construction of their particular flex sensor, seen in Fig. 11.[13] Stiff acetate film provides the backbone of the sensor, and an undescribed "resistive material" is attached to one side. To this material two copper strips are attached, and the resistance between the two copper strips varies when the flex sensor is deformed.

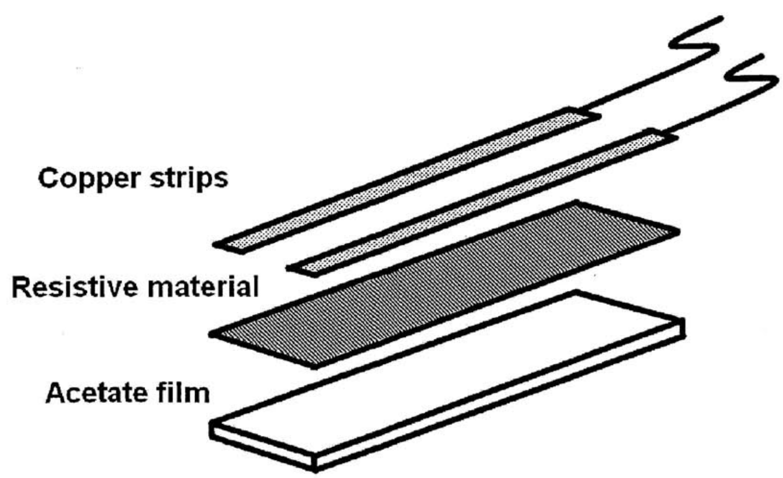

Figure 11: *Construction of the Images Scientific Instruments flex sensor.*

The Images flex sensors appealed to us because they were inexpensive, could be built to a particular size, and appeared to be covered in heat-shrink tubing that could potentially be made waterproof easily. While the construction of the sensor is quite straightforward, the "resistive material" is vaguely-defined. For the sensor to function effectively, the material must be somewhat conductive, offering a certain value of resistance that varies when it is physically deformed. When attempting to build flex sensors with our own material, we tried a variety of plastic, cloth, and paper materials without success. From Images we purchased sheets of the material they use to build their sensors, a single layer of carbon-loaded polyethylene typically used in conductive bags for the electrical industry. [13]

To evaluate the potential application of this type of sensor in our device, it was important to understand how a certain amount of deflection caused change of resistance within the material. To test this, we fixed a flex sensor to a rigid table and varied the amount of the sensor that was hanging off the edge of the table unsupported. The 0.25-inch by 4.5-inch sensor's nominal resistance was measured, and then the sensor was bent by a certain number of degrees. For each of the three different lengths of overhang, the deflected resistance was measured and compared to the original, unbent resistance.

4.1.3 Flex Sensor Results and Conclusions

Fig. 12 displays the results of our investigation. The change in resistance is presented as a fraction of the original, unbent resistance of the flex sensor.

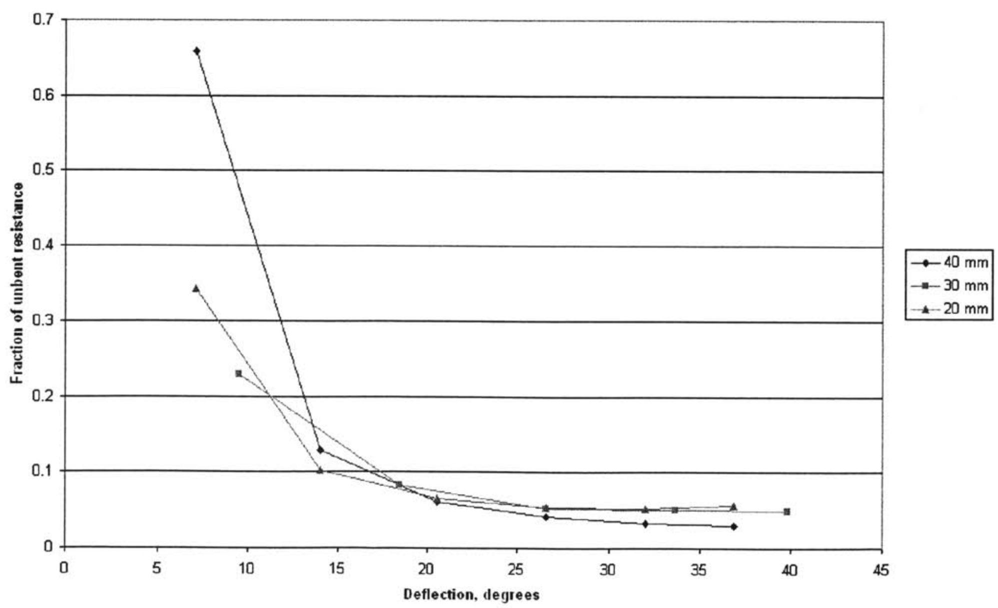

***Figure 12**: Characterizing the resistive material: deflection versus fraction of initial resistance.*

Our results indicated that the flex sensor was particularly sensitive to small deflections – for each overhang, at a deflection of only 15 degrees the resistance was less than 20% of its original value. Larger deflections beyond 20 degrees yielded very little improvement in resistance change – in fact, for deflections beyond this value the flex sensor's resistance was about 5% of its original value.

The results of testing with the carbon-loaded polyethylene were encouraging. Only a small deflection was required to produce a significant change in resistance, so the sensor's backbone material could be reasonably stiff. However, there were concerns about how the deflecting sensor could be implemented in the device's channels. An edge of the material would be anchored in one side of the channel, requiring a certain amount of material between adjacent channels that could be difficult to incorporate into potential designs. The rectangular shape of the flex sensor raised concerns with respect to the manufacturing of channels, as well as sealing them when a pressure gradient was present.

It is a concern that the sensor cells will behave differently in static and dynamic situations. In static interaction, there is a pressure difference within the sensing channel, but no water is able to pass from one end to the other. The forces acting on a sensing material are straightforward. In a dynamic situation, where the sensing material does not seal off the channel, the water is able to move from one end of the channel to the other. Fluid in motion has a lower pressure than at rest, so the size of the pressure gradient is uncertain. This was a large drawback of the flex sensor design, and why it was a concern that the rectangular flex sensor might not be able to seal off the channel effectively. We also noticed hysteresis effects with the flex sensor that would undermine the ability of the sensor to detect leaks with high resolution. The change in resistance was rapid upon deflection, but restoration to original values lagged significantly when unbent.

The flex sensor was ultimately dismissed in favor of a different type of sensor that fit the pressure channels more easily and was non-permeable. While it is possible that the flex sensor could have been implemented, a deflecting silicone membrane appeared to be simpler, more effective at sealing the channel, and just as easy to build for testing.

4.2 A Deflecting Silicone Membrane

The deflecting silicone membrane design is simple, consisting of a membrane of soft rubber mounted in a small section of ½-inch PVC pipe.

4.2.1 Theory of Operation

The silicon membrane sensor unit is mounted rigidly in a channel of the leak-detecting device. Its fit is water-tight, preventing fluid from moving between the regions of high and low pressure. While the fluid is unable to move, the high pressure gradient on the inner edge of the membrane creates a force that acts on the membrane, toward the outer edge of the device as seen in Fig. 13.

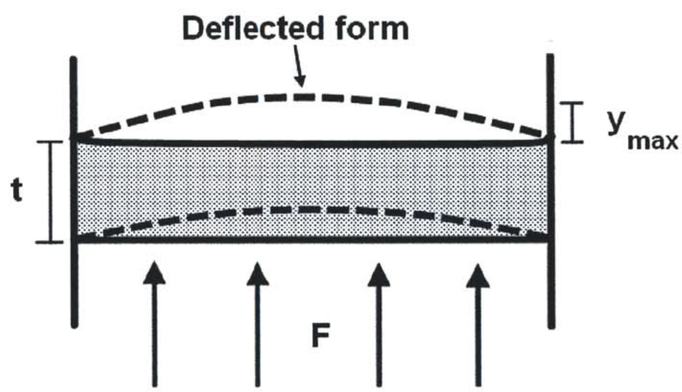

Figure 13: *The force acting on the deflecting membrane sensor causes deflection. This is a side view of a channel.*

The silicone membrane sensor works by measuring a certain deflection of the membrane when a force is applied. The membrane deflects in accordance with the following formula, found in Roark's Formulas for Stress & Strain:[14]

$$y_{\max} = \frac{-\alpha \cdot q \cdot a^4}{E \cdot t^3} \qquad [1]$$

where $y_{\max}$ is the maximum deflection of the membrane; α is a geometry-dependent constant; q is the average force per unit area acting on the membrane; a is the diameter of the membrane; E is the Young's Modulus of the membrane material, and t is the thickness of the membrane.

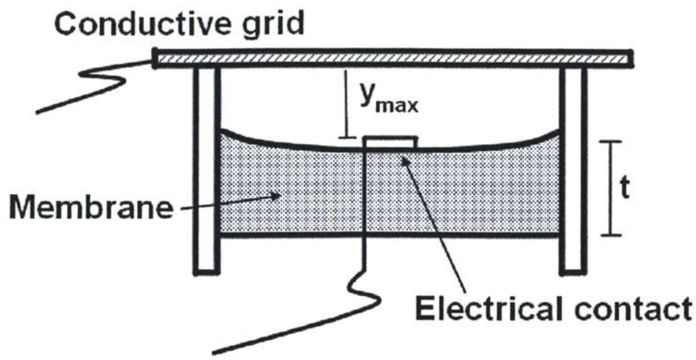

Figure 14: *Side view of the construction of the silicone membrane sensor cell.*

We are building a binary sensor for this application. As show in Fig. 14, the deflecting membrane's outer surface features an electrical contact. A set distance above the unstressed membrane there is a rigid, mesh conductive grid. When the membrane deflects under load, the electrical contact and the conductive mesh grid come in contact and complete an electrical circuit.

A similar principle could be used to create a capacitance change between two parallel plates. A more sophisticated capacitance-based sensor is the subject of research by my peer, graduate student Benny Drescher.

Examining Eq. 1, the load per unit area (pressure) and diameter of the sensor cell are constrained by the size requirements of the sensing device. Three remaining parameters can be varied to "tune" the sensor for our particular application: maximum deflection, Young's Modulus of the membrane material, and the membrane thickness. Maximum deflection is partially limited by the packaging of the sensing cells; I chose to set the value to 2mm in order to reduce sensor size and prevent the membrane from constantly experiencing large-scale deformation, which might decrease accuracy or reduce the life of the sensor cell.

Eq. 1 can be rearranged so that we have an expression for the required thickness of the membrane.

$$t = \left(\frac{-\alpha \cdot q \cdot a^4}{E \cdot y_{\max}} \right)^{\frac{1}{3}} \qquad [2]$$

The material selected for this application was Smooth-On brand Ecoflex 0030 silicon rubber, chosen because it can be mixed and poured to any application, and because its Young's Modulus of 125 kPa set the required membrane thickness to roughly 10 mm, a thickness that works well with the dimensions of our device.[15] Fig. 15 below shows the thickness required for different pressure gradients, calculated with Eq. 2.

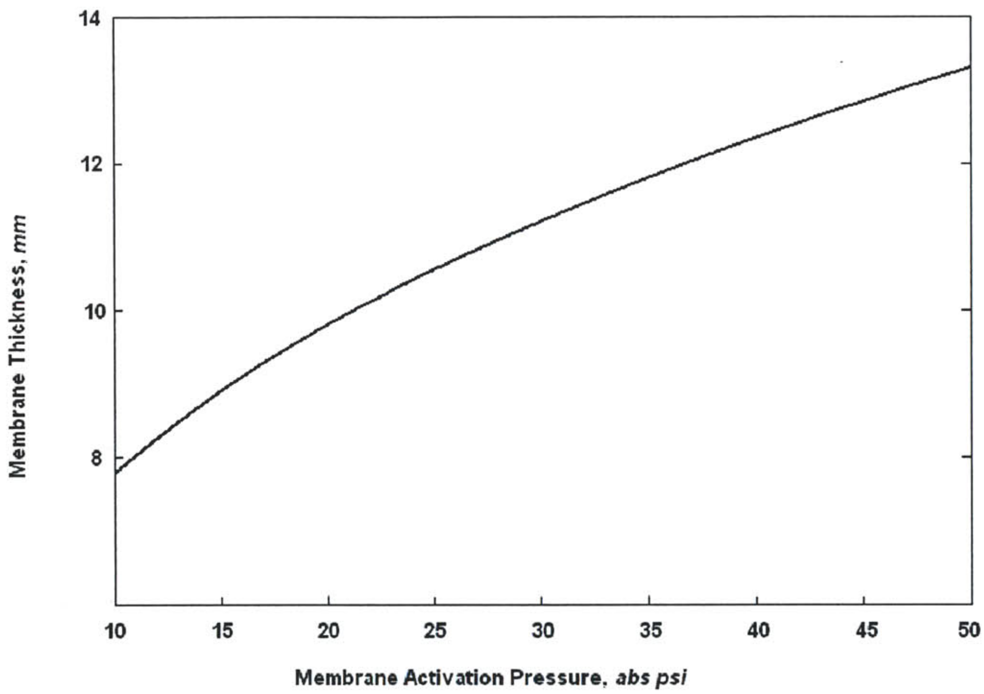

Figure 15: *Required membrane thickness as a function of activation pressure.*

4.2.2 Experimental Setup

Based on the results of Fig. 15, we built four test sensors cells with membrane thicknesses of 9 mm, 10.5 mm, 12 mm, and 13 mm to test the validity of Eq. 2. The sensor cells were built as illustrated in Fig. 14, and then mounted in 2" PVC cap pieces to be installed on a test pressure chamber. Fig. 16 shows a sensor unit mounted in a PVC cap, while Fig. 17 shows the cell mounted in the test chamber.

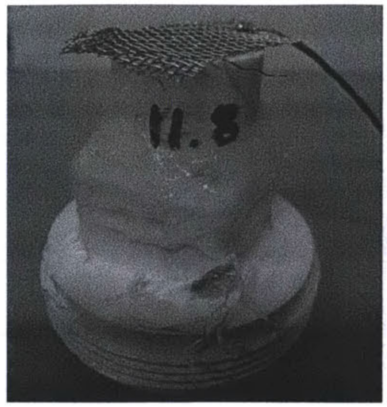

Figure 16: *A membrane sensor cell mounted in a 2" PVC end cap and sealed with silicone.*

Figure 17: *The membrane-cap combination mounted in the pressurized test chamber.*

The test chamber, built by my peer Benny Drescher, is made of 2" PVC pipe, and features a bicycle air valve that is used to pressurize the chamber. A Honeywell 480-2567-ND pressure sensor measures the internal pressure of the chamber; there is a small gap in the chamber that allows pressure to be bled off slowly so that the membrane can be deflected and relaxed multiple times. To conduct a trial, the membrane sensor cell is screwed into the chamber and its leads are attached to a simple circuit. A bicycle pump is used to slowly pressurize the chamber. When electrical contact is achieved the circuit is completed, indicating that the membrane has deflected enough to contact the grid 2 mm away, the pressure readings are recorded. Each membrane sensor cell is cycled eight times, and the pressure at which electrical contact is established and broken is recorded, giving a total of 16 data points. The mean of these readings is the average pressure at which the sensor is activated.

4.2.3 Results and Discussion

Fig. 18 displays the results from the experimental trials alongside the predicted outcomes. It can be seen that, for the thinner three membranes, the correlation was positive. However, the experimental data poorly matches the predicted values. In addition, the 13-mm sensor deflected at a lower pressure than the 12-mm sensor.

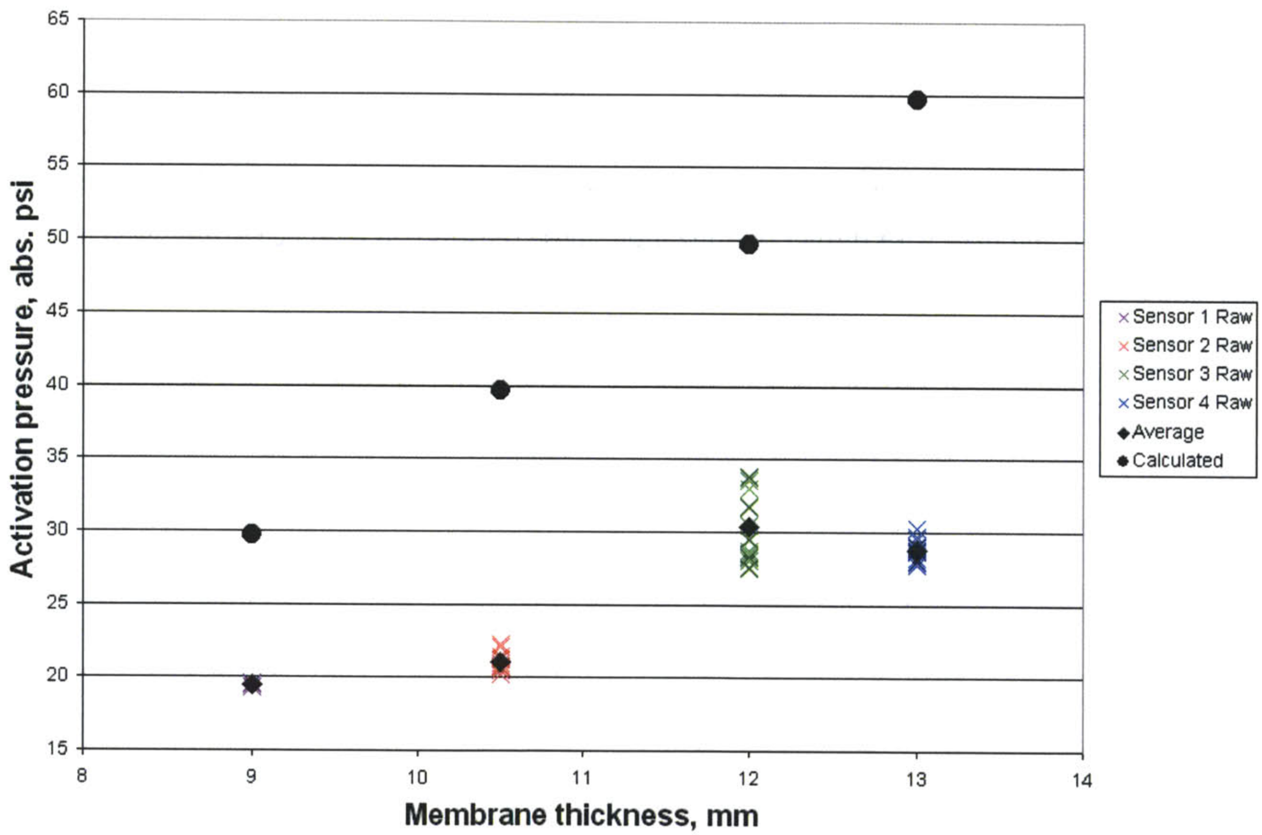

Figure 18: *The results of the membrane deflection tests, compared to the calculated values.*

The lack of correlation between the anticipated values and those obtained in testing can be the result of a few factors. First, it may be the case that Eq. 1 does not accurately describe membrane deflection as it occurs in this scenario. Another possibility is that the Young's Modulus of the Ecoflex 0030 rubber that we mixed was not precisely equal to 125 kPa. While care was taken to ensure that the two ingredients of the rubber compound were mixed in the correct proportion and stirred thoroughly, it could be an effect of the construction or curing process that the Modulus had a different value. All four sensors tested were poured from the same batch of material; if the value of E in Eq. 2 is different from 125 kPa, the thickness-pressure curve would shift vertically. This could potentially explain the disparity between the calculated figures and recorded data.

The performance of the 13-mm sensor is very likely the result of a failure that occurred in testing. Under pressure, the bond between the rubber compound and the interior of the PVC pipe broke, leading to premature electrical contact.

While the correlation between the predicted and obtained values was poor, the behavior of the surviving sensors is encouraging. Their performance indicated that the design itself was feasible; that the rubber membrane physically deflected as anticipated (in shape, if not in relation to input force); and that, with further optimization, these sensors can be successfully used to detect the presence of a pressure gradient.

5 Conclusion

This paper serves as only the first step in the development of an untethered leak-detection device. Much of its focus is on preliminary exploration, material selection, and mechanism design for the sensor cell as a result. While the testing of the deflecting silicone membrane did not match the results predicted using Eq. 1, the general behavior of the sensor and the experience of building and implementation are encouraging enough to recommend continued development. Pressure-difference based sensing is a viable option in leak detection, and the region of leak-associated low-pressure is sufficiently large for detection. The membrane-based contact sensor can be applied to effectively indicate the presence of a pressure gradient. Section 6 covers recommendations for future technology development.

One of the largest problems facing the leak-detecting device is its mobility. The form of the device depends on the solution to this problem, and has an important effect on the way that the sensor cells are integrated. This pursuit, however, is worthwhile. As explained in Section 1.1, the problem of leaking water pipes has considerable effects on civilizations in every part of the world. As the world population increases and urban cities become more populous, the load on an already-strained water distribution network will only increase. Minimizing water loss through leaks will become increasingly important, and an effective method of leak detection will be required.

6 Future Work

Our investigation covered the initial stages of sensor cell development for an untethered pressure difference-based leak detection device. We gathered information concerning the size and shape of a leak-associated low pressure region, and explored different types of sensor before building a deflecting silicone membrane sensor cell.

There are many technical problems to be addressed before an effective leak-detection device can be produced. The next stage of development for these sensor cells would involve evaluating the means by which the cells could be made waterproof. Currently the electrical contacts on the membrane and conductive grid are exposed to the fluid environment, which may lead to corrosion of material over time. While performance would likely not be affected by the presence of water, whose resistance is high, it would be desirable to develop a sensor setup that seals electrical components. Additionally, based on Eq. 1 in Section 4.2.1 and the results described in 4.2.3, the parameters of the sensor could be "tuned" for price and manufacturability. In addition, the membrane sensor cells should be tested in leak conditions, with flow through the pipe, not simply in static fluid conditions.

The shape of the final leak-sensing device, which is primarily defined by the way it navigates pipe networks, has yet to be finalized. It is currently under development by my peer Naomi Zabel. It must be able to move through pipe bends, elbows, and joints without stalling or becoming lodged; at the same time, it must be composed of sensing channels that, as explored in Section 3.1, are as close to the pipe walls as possible. The way that the device integrates the sensing cells examined in this paper depends on the form that Ms. Zabel has generated, and must be addressed in the future.

In addition to the shape of the final device, the means by which it moves through the pipes must be decided. Whether it flows freely, propelled by the movement of the fluid within the pipes, or whether it is self-propelled has not been determined. The physical dimensions and mass of the device will be the relevant factors in choosing a means of propulsion.

Finally, the means by which the device stores and transmits information are undetermined. There are a few possibilities: the device can store information until it is removed from the pipe; it can store information and transmit it out of the network at a certain section of the pipe where a data receiving system is installed; or it can transmit the information wirelessly to an operator in real-time. Which option is pursued will depend on the cost target of the system and limitations of data transmission technology.

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